OVERVIEW

Synopsis

The following excerpt appeared on the poster announcing the workshop:

"The purpose of this workshop is to bring together neutron researchers with special interest in detector instrumentation and experimental needs. Overviews will be given of experimental facilities at the major operating spallation sources in the world. Reviews will be made of the current status of neutron detector technology in use at spallation sources and recommendations for future detector research activities will be an important outcome of the workshop.

The Spallation Neutron Source (SNS) in America is now in planning and design stage. The Japanese Hadron Facility is under consideration for funding and the European Spallation Source (ESS) is the next major planned neutron facility in Europe. It is important that resources for instrumentation are wisely used, and it is the intention of this workshop to provide critical advice for future research efforts.

Attendees are encouraged to present posters that will be on display throughout the workshop."

During the two-and-half day workshop, comprehensive reviews were given of the following spallation source facilities: IPNS at Argonne National Laboratory (plus a preview of the SNS), ISIS at the Rutherford Laboratory in England (plus a preview of the ESS), KENS at KEK in Japan (plus a preview of JHF), and LANSCE at Los Alamos National Laboratory.

This was followed by overview presentations of the present status in three major areas of neutron detector development: "Gas Detectors," "Scintillators" and "Hybrid & Other Technologies."

"An Experimenter's view of the Needs for the Future" was presented by Andrew Taylor, which was followed by an "Open Discussion on Technologies to Pursue for the Next Generation Instruments," moderated by Veljko Radeka. This discussion concluded with some key issues for consideration by the working groups, a) Detector Requirements, b) Detector Technologies and c) Spallation Source Detector Requirements, the outlines being tabulated below.

Working groups were convened to report on each of the three areas of Detector Technology, and the group reports contain detailed recommendations concerning future research and development.

Viewgraphs of all the oral presentations are included, together with highlights from two of the poster presentations.

Finally, group photographs are shown, together with a listing, of the registered participants, including their mailing and e-mail addresses.

Open Discussion on Technologies to Pursue for the Next Generation Instruments

a) Detector Requirements

	Characteristic	Considerations
1	Geometry: Beam, sample and detector	Detector size and shape Position resolution => number of pixels Continuity of sensitive area vs. modularity
2	Time Properties	Timing resolution Counting rate vs. time, space (local/global) Recovery time
3	Uniformity and Stability of Response	Absolute stability over several days or weeks
4	Dynamic Range	In time and position
5	γ sensitivity	
6	DQE	
7	Radiation Effects	
8	Fine Effects (or not so fine)	Effects that one does not like to talk about: blooming, halos, discharges
9	Counting Rate Limits	Detector physics Electronics Readout segmentation
10	Operating Costs & Reliability	

b) Detector Technologies

New Concepts => time scale unknown
Previously used technologies => project schedules possible

	Technology	Considerations
1	Gas Detectors	MSGCs MWPCs
2	Scintillators	New materials Detector configurations, PMs, CCDs
3	Hybrid & Others	$^{157}Gd/CsI$ + MSGC Si/Gd Si/^{10}B

c) Spallation Source Detector Requirements
See table overleaf.

Spallation Source Detector Requirements

	Sample to Detector Distance	Angular Coverage/ Detector Size	Pixel Size	Rate global/local	Stability	Energy Range	Timing Resolution
Single Crystal Diff.	≤ 1 m	2π	≤ 1 mm^2	10^6 / 10^6	H	0.3–5 Å	~ 1 μs
Powder Diff.	1 m	π	5×5 mm^2	10^5	M	0.3–5 Å	~ 1 μs
Disordered	≥ 1 m	π	5×50 mm^2	10^5	VH	0.1–5 Å	~ 1 μs
SANS	2-10 m	1 m^2	1×1 mm^2 ~ 5×5 mm^2	10^6	H – VH	1–20 Å	~ 1 μs
Inelastic-Isotropic	2–6 m	10 m^2	20×20 mm^2	10^4	M	meV–1 eV	~ 1 μs
Inelastic-Single Crystal	2–6 m	10 m^2	20×20 mm^2	10^4 / 10^6	M	meV–1 eV	~ 1 μs
Transmission	NA	50×50 mm^2	~100 μm	10^7	VH	0.1-20 Å	~ 1 μs

WORKSHOP ON NEUTRON DETECTORS FOR SPALLATION SOURCES
Brookhaven National Laboratory, Berkner Hall, Rm. B
September 24-26, 1998
Agenda

Thursday 24th September

07:30-08:45	*Reception Breakfast and Registration*		
08:45	Welcome		P. Paul (BNL)
	DETECTORS AND FACILITIES: Chair, J. Hastings		
09:00	Overview of Detectors		T. Wilpert (HMI)
	Overview of Spallation Facilities		
09:30		IPNS/SNS	K. Crawford
10:00		ISIS/ESS	N. Rhodes
	Coffee Break		
11:00		KENS/JHF	M. Furusaka
11:30		LANSCE	J. Kapustinsky
12:00	*Lunch*		

DETECTOR TECHNOLOGIES PRESENT STATUS: Chairs, G. Smith, J. Hastings

	Gas Detectors	
13:30	H. Okuno (KENS)	^{3}He-Gas Detectors for Future KEK Facilities
13:50	K. Enevoldsen (RISØ)	Presentation of the MicroStrip Gas Counters Developed at Risø
14:10	B. Yu (BNL)	High Precision Thermal Neutron Detector Development at BNL
	Scintillators	
14:30	C. Van Eijk (U. of Delft)	Development of New Inorganic Thermal-Neutron Scintillators
14:50	M. Wright (ORNL)	Current Progress on Scintillation & Semiconductor Area Detector Development at ORNL
	Coffee Break	
	Hybrid and Other Technologies	
15:40	M. Katagiri (JAERI)	Imaging Methods for TOF Detectors
16:00	B. Gebauer (HMI)	Novel Large-area, Low-pressure MSGCs for Thermal Neutron Imaging Using ^{157}Gd/CsI Converters
16:20	C. Petrillo (Perugia)	Si-diode/Gd Detectors for Thermal Neutrons

16:40	H. Shimizu (KENS)	Semiconductor Detectors
17:00	Poster Session	
18:30	*Reception and Dinner - Berkner Hall*	

Friday 25th September

	DETECTORS FOR FUTURE SOURCES: Chair, J. Z. Larese
09:00	An Experimenter's View of the Needs for the Future A. Taylor (ISIS, Rutherford)
10:00	*Coffee Break*
10:30	Open Discussion on Technologies to Pursue for Next Generation Instruments Discussion Leader: V. Radeka
12:00	*Lunch*
13:00	Tour of Instrumentation Division
14:30	Working Groups: Develop Detailed R&D Plans to Meet Future Needs
18:30	*Reception and Dinner - Berkner Hall*

Saturday 26th September

09:00	Reports by Working Groups and General Discussion
12:00	Adjourn - Lunch

Gas Detectors
Report on Working Group

P. Geltenbort (ILL), G.C. Smith (BNL) and B. Yu (BNL)

1. Introduction

The working group considered the gas detector presentations, and noted the properties of gas filled detectors that make them important for neutron scattering experiments:

- good detection efficiency
- good position resolution
- excellent γ-backgound rejection
- two dimensional capability
- long term stability
- design flexibility in size, shape and readout method

With respect to the table of Spallation Source Detector Requirements, gas detectors largely fulfil the conditions of all the research fields except for Transmission, where the pixel size requirement is too stringent. Gas detectors can be particularly advantageous where large angular coverage is important.

2. Present Status

It was clear from the four facility overview presentations that gas detectors are utilized in a great many experiments operating at these existing facilities, and almost certainly represent the highest percentage of all types of detector in use. However, the majority of them are commercial, single wire devices, that either are their own counters, or have one-dimensional position encoding along a resistive wire. Only a small number of companies manufacture two-dimensional gas detectors, or those with large area in a single gas volume. Basic R&D is carried out by a similarly small number of university and laboratory groups around the world.

In the gas detector presentations, Hideki Okuno presented characteristics of gas detectors, and the present and future directions for small, medium and large-scale Position sensitive detectors. Karen Enevoldsen presented the current status of gas detector development at Riso National University, work based on Microstrip Gas Detectors (MSGCs). Bo Yu described the neutron detector development program at Brookhaven, which is based largely on multi-wire detectors. An extra presentation was included at the end by Bruno Guérard, ILL, who gave a summary of his laboratory's MSGC detector development.

An important, inherent property of gas detectors is time resolution that is of the order of 1 μs. Most gas detectors that have been developed for steady state neutron sources are therefore potentially suitable for spallation source experiments. In considering new gas detectors specifically for spallation sources, the time resolution is always available as an intrinsic feature, provided operation is in the pulse counting mode.

Detectors based on neutron absorption with ^3He have reached a level of maturity where efficiency and position resolution is well understood. Pressures of several atmospheres of ^3He and a suitable quench gas can give detection efficiency over 50% for 2-10 Å neutrons, and position resolution limited by gas effects of 1 to 2mm, and sub-mm for small detectors with higher pressures. Regardless of whether multi-wire or MSGC technology is used, the position readout can lead to degradation in resolution performance if it is not properly designed, and this in turn can lead to problems with long term stability if too high a gas gain is required. The readout design is simplest for small detectors, which can also be more easily constructed at higher pressures. RISO, BNL and ILL have all produced detectors with areas of order $100cm^2$ that satisfy the above conditions. Some approaches are different. For example, with MSGCs, RISO and ILL, build detectors with ultra-clean materials and a sealed, static gas volume. For its multi-wire detectors, BNL uses clean materials, but also incorporates a gas recirculating and purification system.

For larger area detectors, $1000cm^2$ or larger, the pressure vessel design requires significantly greater scrutiny than for smaller devices. Large square areas can be achieved through the use of double windows, the outer one being spherical and containing ^4He before the inner window. Long detectors with modest heights can also have very large areas, an approach that lends itself to curvature in one dimension to eliminate parallax over very large angles of coverage. Both BNL and ILL have significant developments of this type of detector. Another approach to covering large areas is concatenation of several smaller area detectors; this obviously will create insensitive regions, but there are certain classes of experiments with symmetry in the scattered spectrum where this may be an efficient solution.

The high rate environment of the SNS will pose special challenges to all detector designers. For gas detectors, this is particularly valid in terms of space charge saturation and stability effects in the detector, and in the readout electronics design. In developments in high energy physics, several detectors have recently been reported that build upon the trend of the MSGC, namely the fabrication of electron multiplying structures by lithography. These devices basically consist of small spacings between the anode amplifying structure and the cathode, and include the Micromegas, CAT (Compteur à Trous), GEM (Gas Electron Multiplier) and Microdot. These developments are encouraging for possible high rate applications, but their stability and long term behavior need far more study for neutron applications.

It was noted that, since gas detectors are regarded as a mature technology, they may not be regarded so favorably for further research and development. The working group made a particular point to caution that not only is research and development important for all types of gas detector, but also beam line planning for the SNS should utilize proven, existing detector technology wherever it is appropriate.

3. Future Activities

Several areas of investigation were identified that, with further study, will help gas detectors play a key role in experiments at the SNS.

• High rate performance. The flux in typical diffraction peaks at even the most powerful steady state reactors does not normally exceed a rate that causes observable pulse height reduction in high performance proportional chambers. Because of the much greater flux expected from the SNS, it will be important to determine the conditions under which pulse height reduction will occur. Some detector parameters on which this will depend include anode charge (i.e. gas gain), anode cathode spacing, and gas pressure. Other gas detector geometries already mentioned, such as the MSGC, CAT and GEM may also help in this area, but it will also be important to bear in mind the requirement for stability and reliability over long periods of time.

MSGCs used for neutron detectors have primarily been constructed from electroconductive glass. This glass appears to possess the right conductivity for establishing reasonably stable operation at high rate, but may require further investigation for the extremely high rates that will be experienced at the SNS. Experimental studies of electron multiplying structures such as Micromegas, CAT (Compteur à Trous), GEM (Gas Electron Multiplier) and Microdot, are required to determine their usefulness for long term, stable neutron detection.

• Aging effects. These are an important concern in gas detectors. When they are operated at large gas gains, it is possible for formation of deposits to occur on the anode wires or strips. It is worth noting that no deposits have been observed in BNL detectors, which are operated at low gas gains of 20-30, after several years of operation at the HFBR. However, one expects them to appear after sufficiently high fluences. It will be necessary to establish quantitatively under what conditions they may occur with the neutron fluence expected at the SNS. This may require reducing the anode gain to extremely low values, with a possible affect on the design of the readout electronics

• High Rate Electronics. Space charge effects at high rates may eventually present a rate limitation for pencil (single diffraction peak) beams, but the global rate limitations for a detector will be determined largely by the position sensing electronics. Electronics will be required that can sustain high rate throughput with an effective dead-time per event that is less than the charge integration time of the cathode and anode signals. This will likely be fulfilled using the latest, high bandwidth ADCs and Digital Signal Processors. Fast data acquisition and analysis systems will be a key requirement in addition.

• Highly Pixelated Detectors. Several emerging technologies will make it possible to develop gas detectors with pixel readout. These include anode amplifying structures in the form of microdots and micropins. However, these will require an even more ambitious electronics development because of the much larger number of channels required.

• Multi-layer Detectors. A method that increases counting rate and reduces parallax error involves placing several layers of gas detectors one behind the other, using a common volume. The depth of each gas layer is small (of order a few millimeters). An appropriate number of layers, at reduced ^{3}He pressure compared with normal, will realize a high efficiency. This approach is similar to that in high energy physics where multi-layers are used to track the trajectory of a charged particle. It is also very comprehensive in the electronics requirement.

• Investigations of low temperature ^{3}He.

4. References

1. G. Cigognani et al., Proc. Int. Workshop on Micro-strip Gas Chambers, Eds. D. Contardo and F. Sauli, Lyons, France, 1995.
2. R.A. Boie et al., Nucl. Instrum. & Meth. 201 (1982) 533-545.
   V.Radeka et al., Nucl. Instr. & Meth. A419 (1998) 642-647.

Scintillators
Report on Working Group

Carel W.E. van Eijk

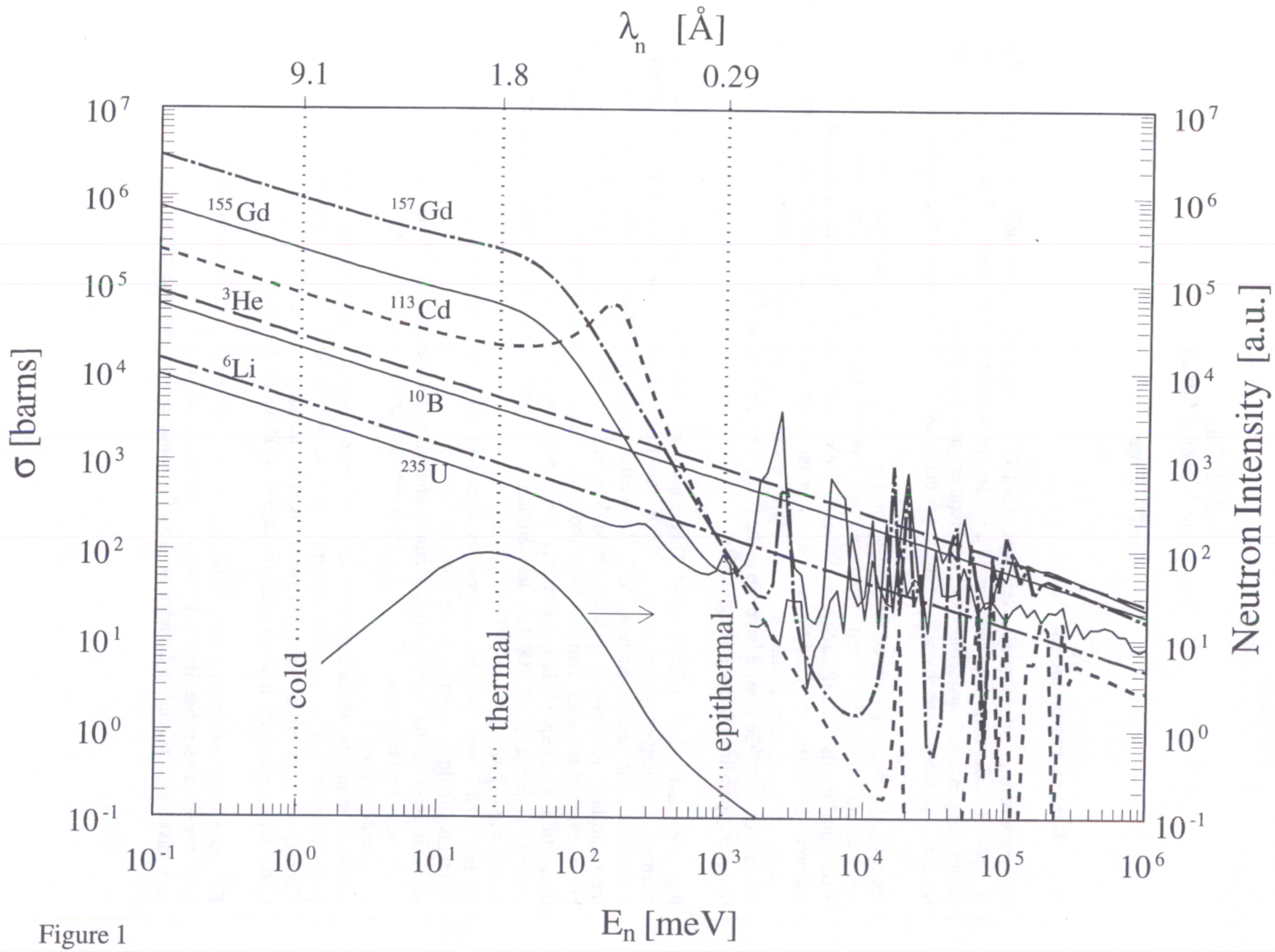
1. General requirements

For many instruments large area detectors of > 1 m^2 are required. Then scintillators existing of a phosphor powder layer kept together by a binder are preferable over crystals. The former are by far less expensive, considering both development and production cost. Crucial is the *index of refraction* of the phosphor which has to match that of the binder for optimal light transport.

For a good efficiency we need *thick layers*: at 1 Å ~ 3 mm for scintillators based on ^{6}Li enriched material and ~ 1 mm for scintillators based on ^{10}B enriched material. At present typical layers of ~ 0.5 mm are used (^{6}LiF/ZnS:Ag). At 0.1Å /1 eV even considerably thicker scintillators are required. Here the study of thermalization in the scintillator and particularly the time until capture (> 1 μs) is important as time resolutions of 1 μs are required. Notice that the cross sections of ^{155,157}Gd show a huge dip in the 0.1Å /1 eV region. See Fig. 1.
In general parallax effects are negligible.

It is important to have a *large signal*. Then gamma ray background suppression will be the least difficult. Consequently the use of ^{6}Li is favourable. This isotope gives 4.8 MeV energy deposition upon neutron capture. ^{10}B is the second best with 2.3 MeV. It should be noticed that the scintillator response in photons per MeV is in general considerably lower for the resulting heavy charged particles than for the photo- and Compton electrons resulting from gamma ray interaction. The required large neutron response makes use of ^{155,157}Gd based scintillators with an electron response of ≤ 100 keV less attractive, in spite of the large cross sections of these isotopes at ~ 1 Å.
To have the lowest possible gamma ray sensitivity the atomic number, Z, of the scintillator elements should be as small as possible.
Another aspect is the intrinsic background radiation of scintillators due to the presence of long-living radioactive isotopes. This background radiation level should preferably be kept at a rate of < 1 count per hour.
Finally it should be noticed that the energy spectrum of a scintillation crystal will show a neutron peak whereas that of a powdersystem like that used at ISIS has a decreasing continuum. Consequently discrimination in the former is easier than in the latter.
Concluding, a gamma /neutron intensity ratio of ~10^{-8} would be perfect.

For wavelength selection a time resolution of 1 μs will suffice. However, considering rates of ≥10^6 per sec a response time of 100 ns would imply a pile up of ≥10%, i.e. dead time problems and wavelength resolution broadening. So a *fast scintillator* response is important.



λn [Å]
9.1
1.8
0.29
σ [barns]
Neutron Intensity [a.u.]
155Gd
157Gd
3He
113Cd
6Li
10B
235U
cold
thermal
epithermal
En [meV]

Figure 1

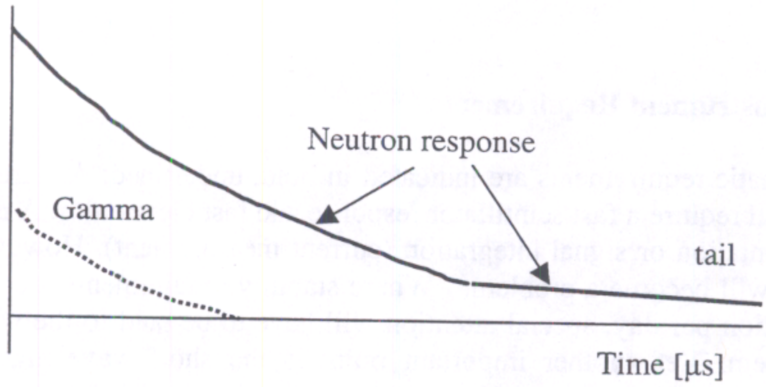


Fig. 2. Signal response of LiF/ZnS:Ag powder + binder

With respect to this last point the signal response of ZnS:Ag should be studied. See Fig. 2 for the signal response of ZnS:Ag powder + binder. It appears that there is a long > 1 μs tail. Ni doping is reported as a possible remedy. Another aspect discussed is the ZnS:Ag response to gamma rays. Response times of 20 ns are reported. This could be used for discrimination. It needs further study as well.

Important is that the emission wavelengths match the light sensors or the wavelength shifters (ORNL system).

As for readout of many pixels we should consider

- -a set of PMs with a coded connection scheme
- -position sensitive PMs
- -silicon diodes (expensive)
- -CCDs give no time information

New concepts should be studied.

Coupling of scintillators with light sensors by

- -fibers — ISIS scheme; ORNL scheme; other
- -Anger camera principle

Readout of a large area pixel (e.g. 20 x 20 mm^2, see Table 1) with a thin (1mm^2) fibre will result in large light loss, even when tapered light guides are used for coupling. Clearly *readout schemes* should be studied and optimized. With respect to this one should not forget rate limitations, i.e. the need of segmentation. Furthermore one should keep in mind flexibility, i.e. modularity, applicability to different geometries, etc.

In general radiation-damage effects will not be important.

We did not consider scintillation in gases. This could be an interesting approach (LANL).

2. The Table of Instrument Requirements

In Table 1 the problematic requirements are indicated in bold, underlined. As already discussed in sect. 1, high rates will require a fast scintillator response and fast electronics. A rate of 10^7 will require detector segmentation or signal integration (current measurement). However, in the last case time information will become a problem. Where stability requirements are Very High, i.e $< 0.1\%$ intensity variation per day, special attention will have to be paid to the whole detection and spectrometer system. Yet another important point is the short wavelength/high energy region. As discussed in sect. 1, thicker detectors will be required for efficient detection.
From the numbers in columns 2, 3 and 4 we find for the number of pixels in a Single Crystal Diffractometer ~ 6×10^6. Obviously this will require a sophisticated readout scheme!

3. Conclusions

Scintillators have a strong potential for thermal-neutron detection.
-In principle large areas can be handled.
-With scintillator powder in a binder this can be realized relatively easy.
-We need smart readout schemes.
-In principle very high efficiency is possible. However, thicker detectors should become available.
-We need a faster response for high rates.
-New (enriched) ^6L or ^{10}B containing scintillator materials have to be studied. Some candidates are:

LiF/ZnS:Ag + codopants
$^6Li_6Gd(BO_3)_3$:Ce
LiF/ZnO:Ga
$LiYSiO_4$:Ce

-Tests of new scintillating powder-binder combinations with various readout schemes have to be performed.

Table 1 Spallation Source Detector Requirements
Scintillators

	Sample to Detector Distance	Angular Coverage/ Detector Size	Pixel Size	Rate Global/local	Stability	Energy Range	Timing Resolution
Single Crystal Diffraction	≤ 1m	2π	≤ 1 mm^2	10^6/**10^6**	H	**0.3** - 5 Å	~ 1 μs
Powder Diff.	1 m	π	5 x 5 mm^2	10^5	M	**0.3** - 5 Å	~ 1 μs
Disordered	≥ 1 m	π	5 x 50 mm^2	10^5	**VH**	**0.1** - 5 Å	~ 1 μs
SANS	2 – 10 m	1 m^2	1 x 1 – ~5 x 5 mm^2	**10^6**	H – **VH**	1 – 20 Å	~ 1 μs
Inelastic-Isotropic	2 – 6 m	10 m^2	20 x 20 mm^2	10^4	M	meV - **1 eV**	~ 1 μs
Inelastic Single Crystal	2 – 6 m	10 m^2	20 x 20 mm^2	10^4/**10^6**	M	meV - **1 eV**	~ 1 μs
Transmission	NA	50 x 50 mm^2	~ 100 μm	**10^7**	**VH**	**0.1** - 20 Å	~ 1 μs

Hybrid and Other Detector Technologies
Report on Working Group

Burckhard Gebauer

Introduction

The working group evaluated four novel detection techniques presented before in the lectures of (i) M. Katagiri (JAERI) on Imaging Methods for TOF Detectors, dealing with a real time scanning and parallel readout method for image plates, (ii) B. Gebauer (HMI) on Novel Large-area, Low-pressure MSGCs for Thermal Neutron Imaging Using ^{157}Gd/CsI Converters, (iii) C. Petrillo (Perugia) on Si-diode/Gd Detectors for Thermal Neutrons and (iv) in a poster of D.E. Holcomb et al. (ORNL) on a High-efficiency, High-speed, Position-sensitive, Energy-resolving Neutron Detector Based Upon a Multilayer Stack of ^{10}B/Si Schottky Barrier Diode Strip Detectors, which was also discussed in the lecture of M. Wright (ORNL). These detectors combine two-dimensional position resolutions of a few tenth of a millimeter or below, a high count rate capacity of $>10^7$/s (for large detectors or detector arrays) and TOF resolutions «1 μs (except for the image plate case). They are all based on using multistep neutron/ eV-electron converter materials (^{157}Gd, ^{10}B, ^{6}Li) in solid form, thus avoiding dislocalization of the position information by long ranges of secondary ions as well as parallax effects.

1. Solid State Neutron Converter Characteristics

Among the utilized converter materials the isotope ^{157}Gd has by far the highest cross section for thermal neutron capture, 255 000 b compared to 3836 b for ^{10}B and 940 b for ^{6}Li, respectively. However, whereas the ^{10}B and ^{6}Li cross sections show a 1/velocity dependence in the full energy range of interest, the ^{157}Gd neutron capture cross section decreases much faster with neutron energy above about 50 meV, intersecting the ^{10}B cross section at 0.45 eV.

After neutron capture in ^{157}Gd the thereby excited resonance state in ^{158}Gd at 7.937 MeV is deexited via a cascade of γ-rays of which the two lowest transitions are appreciably converted, the total percentage of neutron capture events associated with emission of at least one conversion electron being 87.3 ± 2.5 % [1] and the conversion electron spectrum ranging from 29 - 182 keV. The conversion electron lines of the lowest (79.5 keV) transition dominate over the next higher (181.9 keV) transition by a factor 11.2, 32.6 % of the strength of the lowest transition being in the K-shell line at 29 keV [2]. The conversion electrons can be detected either directly, e.g. in silicon detectors, or by amplifying secondary electrons released by them from secondary electron emitter (SEE) surface layers. In ^{157}Gd metal the thermal neutron absorption length and the conversion electron attenuation length, averaged over 4π emission and the full emission spectrum, are 1.3 μm and 11.6 μm [1], respectively, delivering an optimal absorber thickness of 3 μm and about 60 % conversion electron escape efficiency from the converter surfaces per captured thermal neutron.

In ^{10}B the thermal neutron 1/e absorption length is 19.9 μm, to be compared with a range of the faster of the two ions emitted in the $^{10}B(n,\alpha)^{7}Li$ reaction (α particles of 1.472 MeV) of 3.14 μm. In ^{6}Li the thermal neutron absorption length is 230 μm and the range of the faster tritons (2.727 MeV) emitted in the $^{6}Li(n,\alpha)t$ reaction is 130 μm. Thus, due to the unfavorable ratio of converter depth and secondary ion range, ^{10}B converters cannot deliver appreciable neutron detection efficiency unless using multilayer stacks of thin ^{10}B layers sandwiched with thin detectors (or diluted in scintillators). With ^{6}Li converters, on the other hand, up to 60 % detection efficiency can be reached in case of cold neutrons of 10 Å wavelength, using only one converter layer sandwiched between two detectors.

2. Range of Applications and Requirements for the Detectors

Owing to the very high position resolutions of up to 50 μm (quoted as FWHM throughout the paper) achievable with the detector types discussed in the working group, they are all well suited for detection of neutron transmission scattering (neutron radiography and tomography) as well as for neutron reflectometry. In these applications only small detector sizes of 50x50 mm^2 for transmission scattering and 50x200 mm^2 for reflectometry, respectively, are typical and position resolutions of up to 50 μm can immediately be useful. Similar position resolutions can also be utilized for single crystal (e.g. protein) diffraction experiments with adequately small sample sizes, provided that their availability triggers a synergetic enhancement of the development of modern neutron optics, in particular double-focusing monochromators, presently being developed in several laboratories.

On the other hand, during the workshop only moderate pixel size requirements were defined for SNS, extrapolated from present spectrometers, of ≤ 1 mm^2 for single crystal diffraction and ~100 μm for transmission scattering, respectively. For single crystal diffraction, large sensitive detector sizes, covering a solid angle of 2π for ≤ 1 m sample to detector distance, are required. For SNS for transmission scattering as well as for single crystal diffraction experiments, global count rates of 10^7/s were anticipated, whereas for the latter case local count rate limits in a Bragg peak of $\leq 10^6$/s were defined. Therefore, if for a single crystal neutron diffractometer, for instance a Si microstrip detector array with sample to detector distance of 1 m, about 2π solid angle coverage and dimensions of 50 μm x 50 mm for both of the perpendicular x and y strips is considered, about 5×10^6 strips must be read out. Thus, a carefully chosen increase of the strip width, e.g. by factors 2-10, and/or encoding techniques for combined readout of several strips via a common data acquisition channel will be necessary. The required global counting rate of 10^7/s will be compatible with a reduction of the number if independent channels by about a factor 10^3 (for μs shaping times) , however a local counting rate of 10^6/s of one spatially concentrated Bragg peak will set a much more stringent limitation to effective pixel sizes. Although for transmission scattering and reflectometry much smaller detector sizes are necessary, in both cases a similar number of pixels is required with the same counting rates.

Consequently, in particular the development of highly integrated electronics and of a dedicated data acquisition system, adapted to the time-of-flight spectrum delivered by pulsed neutron sources, will be the most demanding task in the SNS detector development program. This is in particular true considering the much smaller manpower available worldwide for neutron detector development compared to high-energy physics, where similar pixel numbers and rates have successfully been handled.

The timing resolution requirements, on the other hand, are much lower than achievable with the detectors discussed (except for image plates), since time frames of 1 μs are appropriate for SNS measurements. Other detector characteristics like the useful energy range, the uniformity and stability of the detector response, the dynamic range in time and position, the sensitivity for background γ-rays and X-rays, the detective quantum efficiency and detector costs and reliability will be shortly discussed, if in question, in the following subsections for the four detector types separately.

3. Si-diode/Gd Detectors

For neutron detection, prototypes of Si microstrip diodes with sizes of a few cm^2 have already been developed and tested with Gd converters [3]. Position resolutions, determined by the pixel size or strip width, of 50 μm can be reached. As known from the inner trackers of high energy physics colliders, large-area arrays of Si detectors can be set up with pixel numbers exceeding those necessary for neutron scattering experiments, however with much more resources than presently available. Thus, conducting collaborative work with experienced, strong groups from high-energy physics is considered particularly mandatory for development of large-area Si detector arrays.

Using highly enriched ^{157}Gd converter layers, sandwiched between two single crystal diodes, about two thirds of the conversion electrons escaping from the converter surfaces can be detected, since with typical thresholds given by noise of 40 keV the K-line at 29 keV is lost. Taking the strong decay of the neutron capture cross section with energy and the conversion electron attenuation in thicker ^{157}Gd layers into account, practical short wavelength limits of application will probably be rather 0.5-0.9 Å (0.1-0.3 eV) than lower, whereas 0.3 Å (0.9 eV) and 0.1 Å (8 eV) were considered as limits required for single crystal diffraction and transmission scattering spectrometers for SNS, respectively. In order to increase detection efficiency for short wavelength, detector stacks with n converter layers ($n \leq 5$-10) sandwiched between diodes should also be considered. Greater numbers n will be very costly, since due to noise, limiting the detection of conversion electrons, the diodes must probably be read out individually. The development of highly-integrated low-noise charge-sensitive preamplifiers for high-capacitance detectors will thus be of greatest importance and should be conducted in an international collaboration combining the efforts of groups working in the field presently.

Using Gd converters with Si detectors or detector stacks, background from γ-rays and X-rays (especially from filling the K-shell vacancies after conversion electron emission) with origin from the converter as well as from external sources will be present, which however can be mostly discriminated, if above threshold, with proper gating on the energy spectra. Due to the noise problem there are also questions whether very high stability and uniformity of response can be achieved over days and among the many strips and individual diodes of the array. However, similar problems had to be faced in high energy physics applications earlier.

4. Si-diode/^{10}B Detectors

Owing to the higher number of charge carriers released by the α and ^{7}Li secondary ions from ^{10}B converters in silicon, compared to conversion electrons, the signals can be less limited by noise. However, due to the small ranges of secondary ions in ^{10}B, only very thin converter layers can be used, sandwiched with diodes, and due to the smaller neutron capture cross section of ^{10}B (for E_n < 0.45 eV relative to ^{157}Gd), multilayer detector stacks with very many converter layers will be necessary in order to achieve good detection efficiency. In principle, for the highest neutron energies of interest better detection efficiency can be attained with ^{10}B than with ^{157}Gd; however, even for detection of 0.1 eV (0.9 Å) neutrons it was proposed by ORNL to use 85 layers of 1 μm thick ^{10}B strips (as converter and for x localization), sandwiched each with two Si Schottky barrier diodes of 8 μm thickness (plus 1 μm thick Al strips for y localization), in order to achieve 90 % detection efficiency. With such thin detectors, noise will be important for large detector areas and even more if stacks of detectors will be commonly read out. Thus, the number of diodes which can be grouped together will be very limited, and the readout electronics will be very costly for the envisaged number of multilayers in a detector stack for large arrays. The dead space needed for readout at the edges of the individual detector stacks has also to be taken into account.

5. ^{157}Gd/CsI Converters in Combination with Low-pressure Microstrip Gas Chambers

At HMI Berlin a novel type of large-area (570x570 mm^2), high-resolution neutron imaging detectors is being developed [1], comprising a thin composite ^{157}Gd/CsI converter foil and two fourfold segmented planes of novel robust low-pressure microstrip gas chambers (MSGC) either side of the converter. The fast ^{157}Gd conversion electrons liberate in a cascade via δ electrons well localized (~μm) eV-electrons on the surface of the SEE coated converter. Normal as well as porous SEE layers will be investigated, the latter being known for higher extractable eV-electron yields. Thus, with the MSGCs being capable of reaching single electron detection efficiency in a low-pressure two-stage amplification mode (with avalanche multiplication commencing at the converter surfaces), full detection efficiency for conversion electrons penetrating the converter surfaces is expected. For the two-dimensional MSGCs a large-area multilayer technology on glass is being developed. By comprehensive modeling, in particular the MSGC design was optimized for low-pressure operation and 2D-readout.

The intrinsic x and y position resolutions of the large-area MSGCs with anode spacing 635 μm are estimated, owing to diffusion, with 100 μm using interpolating strip readout techniques. In order to overcome possible limitations in the local count rate capability due to UV and ion feedback to the converter, an additional gas electron multiplier (GEM) foil can be inserted above the MSGC. Optimized delay line readout techniques, using impedance matching transistor circuits at the strips, and highly integrated, fast data acquisition cards are being developed, compatible with

≤300 μm position resolution and count rates ≥3x10^6/s per detector and ≥10^6/s per segment. If, for instance for a single crystal diffraction spectrometer, a detector array covering 2π with 1 m sample to detector distance is set up, about 24 detectors of the present size are needed. (The MSGC design can also be easily adapted to different geometrical boundary conditions.) Thus, for single crystal diffraction with SNS, with this detector type all requirements with regard to size, resolution and counting rates can be met economically with delay line readout, since only 32 readout channels are needed per large-area fourfold segmented detector and since the costs per area for the large-area MSGCs are low in series production. For instance, SANS spectrometers can also be equipped with this detector type. For small size transmission spectrometer detectors, single strip readout with 100 μm resolution would be preferable. However, for applications requiring intermediate detector areas and count rates, e.g. one MSGC segment of the present size (285x285 mm^2) can be used, as an economical high resolution detector, with 4-fold segmented, 4-fold faster delay lines, delivering resolutions <200 μm and count rates >3x10^6/s.

The main neutron wavelength range of interest for this detector type will be above 0.5 Å (as for Si/^{157}Gd detectors). Detector stacks with n≤5-10 converter layers can also be developed using robust MSGC plates of 1 mm thickness (compared to 0.5 mm used in particle physics for MSGCs of the same size). Owing to the novel 2D-MSGC multilayer design, double-sided detector plates can be made, thus minimizing the stack thickness and neutron losses.

Open questions remaining for this detector type concern its γ-ray sensitivity and the long-term stability and uniformity particularly of porous SEE converter layers. However, owing to the two-stage amplification mode applied, the γ-ray sensitivity in the detectors is restricted to the very thin converter layer; and γ-rays from the conversion process itself deliver background only if emitted in the very small solid angle of the converter plane. Porous layers might allow γ-ray discrimination. Its sensitivity against UV photons from the avalanches can be reduced by appropriate surface layers. The uniformity requirements for the converter layers can be met by presently developed evaporation techniques.

6. Image plates with real time scanning and parallel readout

The fourth detector type discussed utilizes image plates in combination with a fast real time scanning system with a parallel readout method based on a streak camera method. With 1000 lines per plate position resolutions of 200 μm and 1 mm and readout times per line of 2 μs and 10 μs are achieved for 200x200 mm^2 and 1x1 m^2 image plates, respectively. The total readout times per plate of 2 and 10 ms, respectively, are, however, incompatible with time-of-flight tagging for SNS, requiring 1 μs timing resolution. On the other hand, these detectors can be used for all types of spectrometers not depending on TOF resolution. The global and local counting rates handled are much higher than required. On the other hand, image plates are known for relatively high γ-ray sensitivity due to the heavy elements contained. The detective quantum efficiency is restricted to ≤35 % due to light detection.

7. Comprehensive Conclusions

The four novel high-resolution neutron detection methods discussed in the working-group all represent potentially very valuable additions to the presently applied 'standard' detector types. They are, however, presently not considered for replacing 'standard' detectors, for instance, for inelastic scattering applications, requiring for SNS detector sizes of 10 m^2 and pixel resolutions of only 20x20 mm^2, although their production costs strongly depend on the number of readout channels decreasing to 25,000 in the mentioned application for single pixel readout. The increase of noise with area should, however, also be taken into account.

The most demanding tasks for developing large-area Si detector systems for future pulsed neutron sources concern the development of highly-integrated low-noise (maybe also cooled) charge sensitive preamplifiers and furthermore of a versatile data acquisition system with appropriate timing properties. Both tasks are best conducted in international collaborations. On the other hand, with the MSGC and image plate detectors presented, probably most of the high resolution detector tasks required for SNS can more economically be fulfilled on the basis of the presently developed electronics, data acquisition and readout techniques. However, in view of open questions and prior to decisions, results from 2-3 years more development work, in parallel for all detector techniques, should better be awaited.

An essential common task remaining for Gd converter detectors is the long-term and safe supply with about 90 % enriched ^{157}Gd, which is probably also best achieved in an international collaboration.

[1] B. Gebauer et al., Nucl. Instr. and Meth. A 392 (1997) 68 and A 409 (1998) 56.
[2] R.C. Greenwood et al., Nucl. Phys. A 304 (1978) 327.
[3] C. Petrillo et al., Nucl. Instr. and Meth. A 378 (1996) 541.